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Search for a Heavy Bottom-like Quark in pp Collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration*

Abstract

A search for pair-produced bottom-like quarks in pp collisions at $\sqrt{s} = 7$ TeV is conducted with the CMS experiment at the LHC. The decay $\mathrm{b}' \rightarrow \mathrm{tW}$ is considered in this search. The $\mathrm{b}'\overline{\mathrm{b}}' \rightarrow \mathrm{tW}^-\overline{\mathrm{t}}\mathrm{W}^+$ process can be identified by the distinctive signature of trileptons and same-sign dileptons. With a data sample corresponding to an integrated luminosity of 34 pb^{-1}, no excess above the standard model background predictions is observed and a b' quark with a mass between 255 and 361 GeV/c^2 is excluded at the 95% confidence level.

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*See Appendix A for the list of collaboration members

The standard model with three generations of quarks describes remarkably well almost all particle physics phenomena observed to date. Although adding a fourth generation of massive fermions is an obvious extension of the model, it became less popular when limits were obtained on the number of light neutrino flavours [1–5]. In addition, precise measurements of the electroweak parameters disfavour such a possibility [6, 7]. Recently, however, there has been renewed interest in the fourth generation [8–12]. Indirect bounds on the Higgs boson mass can be relaxed [13, 14], and an additional generation of quarks may possess enough intrinsic matter and anti-matter asymmetry to be relevant for the baryon asymmetry of the Universe [15].

A search for a heavy bottom-like quark (b') is presented in pp collisions at a centre-of-mass energy of 7 TeV with the Compact Muon Solenoid (CMS) detector at the large Hadron Collider (LHC). The decay chain $\mathrm{b}'\overline{\mathrm{b}}' \rightarrow \mathrm{tW}^-\overline{\mathrm{t}}\mathrm{W}^+ \rightarrow \mathrm{bW}^+\mathrm{W}^-\overline{\mathrm{b}}\mathrm{W}^-\mathrm{W}^+$ is expected to be dominant if the mass of the b' quark ($M_{\mathrm{b}'}$) is larger than the sum of top-quark and W-boson masses [16]. A b' mass below this threshold is disfavoured by results from several previous experiments [17]. As each W boson can decay leptonically into $\mathrm{e}\nu$ or $\mu\nu$ in 22% of the cases, the full decay chain may lead to distinctive signatures with two same-sign isolated leptons or three isolated leptons in the final state, which covers 7.3% of the total decays and is expected to happen very rarely in the standard model. A similar search in these decay channels has been carried out by the CDF experiment [17], setting a lower limit of 338 GeV/c^2 at the 95% confidence level (CL) on the mass of b' quark.[1]

The central feature of the CMS detector is a large-solid-angle magnetic spectrometer, with an axial magnetic field of 3.8 T provided by a superconducting solenoid. Charged particle trajectories are measured by a silicon pixel detector and strip tracker. A lead tungstate crystal electromagnetic calorimeter (ECAL), with a lead-silicon preshower detector in the end-caps, and a brass/scintillator hadron calorimeter (HCAL) are placed outside of the tracker, which altogether provide high resolution measurements for electrons/photons and hadronic jets. The hermetic design of the detector allows good measurement of missing transverse energy. Muons are detected by the tracker and a gas-ionization detector embedded in the steel magnetic field return yoke. A detailed description of the CMS detector can be found in Ref. [19].

This analysis is based on a data sample corresponding to an integrated luminosity of 34 pb^{-1} recorded during 2010 run. A two-level trigger system [20] selects events for further analysis. The events in this search are selected by requiring the presence of at least two electrons or at least one muon in the trigger. Given the trigger efficiencies measured in data for single-trigger objects, the trigger efficiency for the final state in the kinematic region of the off-line analysis has been determined to be more than 99% from simulation studies.

Candidate muons are reconstructed with a global fit of trajectories using hits in the tracker and the muon system. Muons are required to have transverse momenta $p_{\mathrm{T}} > 20$ GeV/c and $|\eta| < 2.4$, where η is the pseudorapidity, defined as $\eta = -\ln[\tan\theta/2]$ and θ is the polar angle relative to the counterclockwise proton beam direction as measured from the nominal interaction vertex. As discussed in Ref. [21], the muon candidate must be associated with hits in the silicon strip and the pixel detector, the segments in the muon chamber, and have a high-quality global fit to the track trajectory. The efficiency for these muon selection criteria is 99% or higher. In addition, the track is required to be consistent with originating from the primary interaction vertex.

Reconstruction of electron candidates starts from clusters of energy deposits in the ECAL, which are then matched to hits in the silicon tracker. Electron candidates are required to have

[1] A new analysis from CDF, in the lepton plus multijet channel, sets the b' quark mass limit at 372 GeV/c^2 [18].

$p_T > 20$ GeV/c. Candidates are required to be reconstructed in the fiducial volume of the barrel ($|\eta| < 1.478$) or in the end-caps ($1.55 < |\eta| < 2.4$). The electron candidate track is required to be consistent with originating from the interaction vertex. Electrons are identified using variables which include the ratio between the energy deposited in the HCAL and the ECAL, the shower width in η, and the distance between the calorimeter shower and the particle trajectory in the tracker, measured in both η and azimuthal angle (ϕ). The selection criteria are optimized [22] to reject the background from hadronic jets while maintaining an efficiency of 85% for the electrons from W or Z decays.

Electrons and muons from $W \to \ell\nu$ ($\ell = e, \mu$) decays are expected to be isolated from other particles in the detector. A cone of $\Delta R < 0.3$, where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, is constructed around the lepton candidate direction. The scalar sum of the track transverse momenta and calorimeter energy deposits inside the cone projected onto the transverse plane is calculated, excluding contributions from the lepton candidate. A barrel (end-cap) electron candidate is rejected if this scalar sum exceeds 9% (6%) of the candidate p_T, while the scalar sum for a muon candidate is not allowed to exceed 20%. Electron candidates are further required to be separated from the selected muon candidates; any electron candidate within a $\Delta R < 0.1$ cone of a muon candidate is rejected to remove misidentified electrons due to muon bremsstrahlung. Electron candidates which are identified as coming from photon conversions are also rejected.

Hadronic jets are clustered from the particles reconstructed with an optimal use all CMS subdetectors by the particle-flow global event reconstruction described in Ref. [23–26], with the anti-k_T algorithm [27]. The energy calibration [28] is performed separately for each particle type, the resulting jet energies require only a small correction accounting for thresholds and residual inefficiencies. Jet candidates are required to have a minimum p_T of 25 GeV/c and $|\eta| < 2.4$. Neutrinos from W boson decays escape the detector and thus produce a significant energy imbalance in the detector. An important quantity is the missing transverse energy, $\not\!\!E_T$, which describes the imbalance of detected energy perpendicular to the beam direction. It is determined as the vectorial sum of the transverse momenta of all particles reconstructed by the particle-flow algorithm [25, 29].

Events are required to have at least one well reconstructed interaction vertex [30]. Events with two same-sign leptons or with three leptons (with two of them are oppositely charged) are selected. Events with fewer than four (two) jets are rejected for the same-sign dilepton (trilepton) channel. In addition, events with an oppositely-charged muon or electron pair with $|M_{\ell^+\ell^-} - M_Z| < 10$ GeV/c^2 are rejected in order to suppress the background from Z decays. The backgrounds due to charge misidentification are substantially larger for electrons than muons, thus events with same-sign electron pair with $|M_{e^\pm e^\pm} - M_Z| < 10$ GeV/c^2 are also discarded. For each event, the scalar quantity $S_T = \sum p_T(\text{jets}) + \sum p_T(\text{leptons}) + \not\!\!E_T$ is determined and a minimum S_T of 350 GeV is required.

Selection efficiencies for signal events are estimated using samples simulated with the MADGRAPH/MADEVENT generator (v4.4.26) [31] with up to two additional partons in the hard interactions. The events are subsequently processed with PYTHIA (v6.420) [32] to provide parton showering and hadronization of the particles, and then passed through a simulation of the CMS detector based on GEANT4 [33]. The signal efficiency varies from 3.1 to 4.6% for b′ masses between 300 and 500 GeV/c^2. These efficiencies include the W decay branching fractions. The jet multiplicities for the trilepton and same-sign dilepton channels are shown in Fig. 1. The distributions of dilepton invariant mass $M_{\ell\ell}$ and S_T are presented in Fig. 2. The expected distributions of the b′ signal are normalized with the production cross section calculated at the next-to-leading order (NLO) in α_s [34], for a b′ with 400 GeV/c^2 mass.

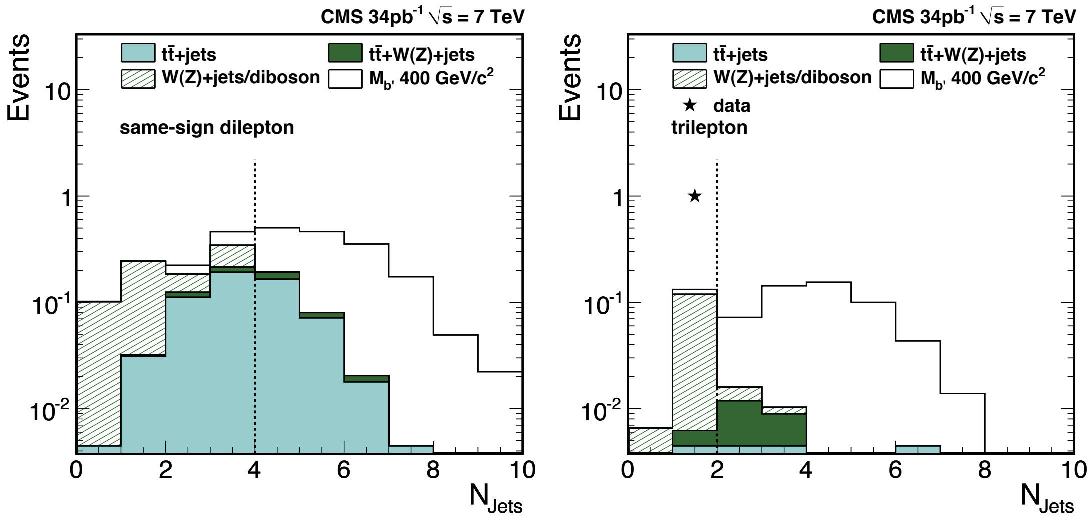

Figure 1: Jet multiplicity distributions for the same-sign dilepton channel (left), and the trilepton channel (right). The star in the right plot represents the single measured event, which fails to satisfy the requirement on jet multiplicity. The open histogram is the signal contribution expected from a b′ with $M_{\mathrm{b}'} = 400\,\mathrm{GeV}/c^2$. The light blue and dark green filled histograms show the contributions from $\mathrm{t\bar{t}}$ + jets and $\mathrm{t\bar{t}} + \mathrm{W(Z)}$ + jets respectively. The shaded histogram represents electroweak processes (W(Z) + jets, dibosons). All selections are applied except the one corresponding to the plotted variable. The vertical dotted lines indicate the minimum numbers of jets required in events selected for each of the channels.

The expected yields and efficiencies for signal and background are summarized in Table 1. The background contributions from $\mathrm{pp} \to \mathrm{t\bar{t}}$ + jets and W/Z + jets are normalized to the CMS measured inclusive $\mathrm{pp} \to \mathrm{t\bar{t}}$, W, and Z cross sections [35, 36]. The simulated samples for $\mathrm{pp} \to \mathrm{t\bar{t}}$ + jets and W/Z + jets processes include initial state b and c quarks in the hard interactions. Production of dibosons is estimated with NLO cross sections given by MCFM [37]. The $\mathrm{t\bar{t}}$ + W/Z and same-sign WW + jj processes are calculated using the MADGRAPH generator at leading order (LO) in α_s. The total background yield is estimated to be 0.33. The only dominant background contribution comes from $\mathrm{pp} \to \mathrm{t\bar{t}}$ + jets events; contributions from other processes are very small.

For the same-sign dilepton channel, there are two types of $\mathrm{t\bar{t}}$ background: single-lepton $\mathrm{t\bar{t}}$ events with an extra misidentified or non-isolated lepton, or dilepton $\mathrm{t\bar{t}}$ events with a charge-misidentified electron. Backgrounds are estimated from data as follows.

Leptons chosen with relaxed selection criteria are denoted as “loose” muon or “loose” electron. Leptons chosen with the full selection criteria defined above are denoted as “tight” muons and “tight” electrons. The background events with a misidentified or non-isolated lepton are estimated using a control region with one tight lepton and one loose lepton, with the rest of the selection criteria exactly the same as for signal. The background contribution is calculated from the yields observed in the control regions multiplied by the ratios of the number of electrons or muons passing tight and loose cuts. These ratios are determined from data by taking the ratios between the number of events in the control region with two loose leptons, and the control region with one loose plus one tight lepton. The background contribution from electron charge misidentification is determined from control regions with oppositely-charged electron pairs or from e-μ events. The charge misidentification rate ($0.6 \pm 0.1\%$) is determined by measuring the Z boson events reconstructed using two electron candidates with the same electric charge, and

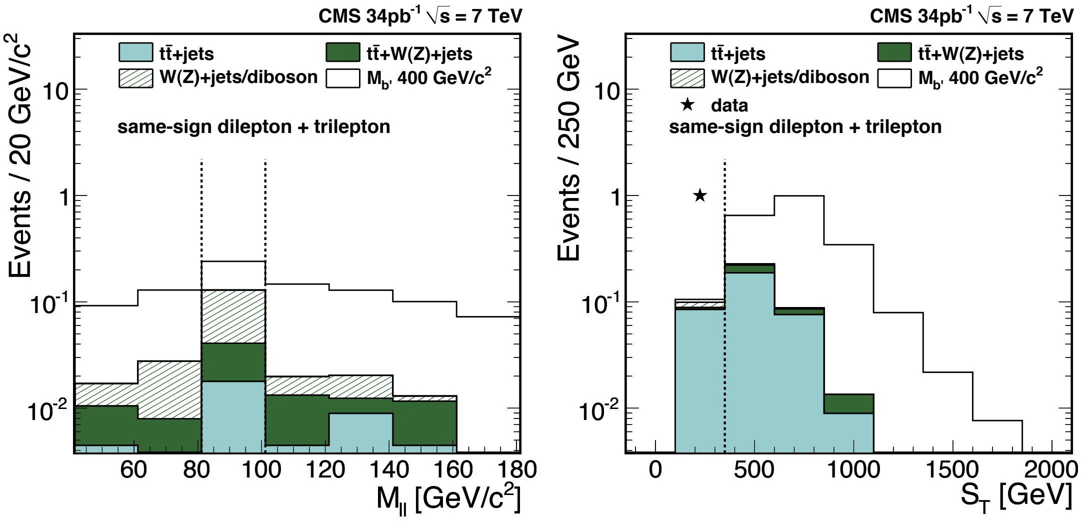

Figure 2: The invariant mass distribution (left) of two muons with opposite charges or electrons of any charge, $M(\ell\ell)$, and the S_T distribution (right) including same-sign dilepton and trilepton channels. The star in the right plot represents the measured event, which fails to satisfy the requirement on S_T. The open histogram is the signal contribution expected from a b$'$ with $M_{b'} = 400\ \text{GeV}/c^2$. The light blue and dark green filled histograms show the contributions from $t\bar{t}$ + jets and $t\bar{t}$ + W(Z) + jets respectively. The shaded histogram represents electroweak processes (W(Z) + jets, dibosons). All selections are applied except the one corresponding to the plotted variable. Events with an electron pair or an opposite sign muon pair, with $M(\ell\ell)$ falling in the region defined by the vertical dotted lines on the left plot, are rejected in order to suppress the background from Z events. The vertical dotted line in the right plot indicates the lower S_T threshold used in the analysis.

Table 1: Summary of expected signal and background production cross sections, selection efficiencies ϵ, expected yields, and the observed event yield in data. The cross sections are obtained from leading order predictions, next-to-leading order predictions, or CMS measurements.

Process	Cross section	ϵ [%]	Yield
$b'\bar{b}'$, $M_{b'} = 300$ GeV/c^2	7.29 pb (NLO)	3.08	7.7
$b'\bar{b}'$, $M_{b'} = 350$ GeV/c^2	2.94 pb (NLO)	3.75	3.8
$b'\bar{b}'$, $M_{b'} = 400$ GeV/c^2	1.30 pb (NLO)	3.99	1.8
$b'\bar{b}'$, $M_{b'} = 450$ GeV/c^2	0.617 pb (NLO)	4.34	0.91
$b'\bar{b}'$, $M_{b'} = 500$ GeV/c^2	0.310 pb (NLO)	4.58	0.49
$t\bar{t}$ + jets	1.9×10^2 pb (CMS)	4.1×10^{-3}	0.27
$t\bar{t}$ + W + jets	0.144 pb (LO)	0.67	0.033
$t\bar{t}$ + Z + jets	0.094 pb (LO)	0.50	0.016
W + jets	3.0×10^4 pb (CMS)	$< 1.0 \times 10^{-5}$	< 0.11
Z + jets	2.9×10^3 pb (CMS)	$< 9.2 \times 10^{-5}$	< 0.09
WW	43 pb (NLO)	$< 8.2 \times 10^{-4}$	< 0.012
WZ	18 pb (NLO)	$< 8.1 \times 10^{-4}$	< 0.005
ZZ	5.9 pb (NLO)	3.0×10^{-3}	0.006
Same-sign WW + jj	0.15 pb (LO)	3.9×10^{-2}	0.002
Background sum	-	-	0.33
Data-driven background yield	-	-	0.32
Observed yield in data	-	-	0

is normalized to the yield of $Z \to e^+e^-$ events.

For the trilepton channel, the background yield in the signal region is estimated using a control region with the same criteria as for the signal, but requiring only two leptons with opposite charges. The normalization between the background in the signal region and the background in the control region is determined from simulations.

The background yield in the signal region, including both trilepton and same-sign dilepton channels, is estimated to be 0.32. The systematic uncertainties on the $t\bar{t}$ background estimations for the same-sign dilepton channel were evaluated using a mixture of simulated samples. The normalization for each physics process in the simulated events is derived from the cross sections. Applying this estimation procedure to the samples of simulated events gives an estimated background of 0.21 events. This is in good agreement with the figure of 0.33 events obtained by counting directly the number of simulated background events satisfying the signal selection. The difference between these two yields is included in the systematic uncertainties. The background estimation procedure for trilepton events is assumed to have a systematic uncertainty of $\pm 100\%$ on the simulated normalization ratio. The sum of these two uncertainties, which arise from the bias of control-region methods, provide the dominant uncertainty of 56% on the background yield.

The relative uncertainty on the integrated luminosity measurement is estimated to be 11% [38] and is included in the limit calculations. The effect of this uncertainty in the background estimation cancels when the absolute normalization of backgrounds are taken from the measured yields in the control regions. The statistical uncertainties on the yields in the control regions are included in the uncertainty on the backgrounds. The QCD multijet contribution is estimated to be smaller then 0.09 events, and considered as a systematic uncertainty of 29% on background

Table 2: Summary of relative systematic uncertainties for signal selection efficiencies ($\Delta\epsilon/\epsilon$) and for background estimations ($\Delta B/B$). The ranges represent the dependence on the input b' mass.

	$\Delta\epsilon/\epsilon$ [%]	$\Delta B/B$ [%]
Accuracy of control-region method	-	56
Norm: QCD multijet	-	29
Norm: $t\bar{t}+$jets	-	0.5
Norm: $W(Z)+$jets	-	1.0
Norm: dibosons	-	0.9
Norm: other processes	-	5.5
Jet energy scale	1.1 – 2.1	1.0
Jet energy resolution	0.1 – 0.6	1.5
Missing energy resolution	0.1 – 1.2	5.6
Lepton selection	13	1.5
Pile-up	1.0 – 1.2	< 0.1
PDF	0.5 – 1.0	1.0
Control region statistics	-	13
Simulated sample statistics	2.4 – 3.0	-
Total	13	65

estimation. The uncertainties on the background cross sections are included by varying the normalization on the relevant processes as follows: ±39% for $t\bar{t}+$jets [35], ±3% (±4%) for W (Z) [36], ±(27 to 42)% for dibosons, and ±50% for other processes. Lepton selection efficiencies are measured using inclusive Z samples; the resulting differences between data and simulated samples are smaller than 2%. An additional systematic uncertainty was assigned with a magnitude of 50% on the efficiency difference between simulated Z and b' samples due to the effects of different event topologies. This results in 5.8% and 5.4% uncertainties for the electrons and muons, respectively. Weighted averages including trilepton and same-sign dilepton final states in the appropriate proportions of selected muons and electrons result uncertainties of 13% and 1.5% in signal efficiency and background estimation, respectively. Uncertainty sets given by CTEQ6 [39] are used to determine the uncertainties from parton distribution functions (PDFs). Weights for each simulated event are recalculated, and the variations are summed in quadrature. The systematic effects of the jet energy scale uncertainty, jet resolution, $\not{E}_T$ resolution, and jets from pile-up are found to be small [28, 29]. The total uncertainties on the signal selection efficiency and on the background estimation are evaluated to be 13% and 65%, respectively, and are summarized in Table 2.

The background yield in the signal region is 0.32 with a total relative uncertainty of 65%. No events are observed in the data, which is consistent with the background expectation. An event is found below the S_T threshold in the same-sign dilepton channel (Fig. 2), and another event is rejected by the jet multiplicity requirement in the trilepton channel (Fig. 1). These two events are consistent with the expected total background yield of 0.69, if the requirements on S_T and jet multiplicity in trilepton channel are relaxed to 200 GeV/c^2 and 1, respectively.

For each b' mass hypothesis, cross sections, selection efficiencies and associated uncertainties are estimated (table 1). From these, from the estimated background yield and zero selected events, upper limits on $b'\overline{b}'$ cross sections at the 95% CL are derived using a Bayesian method with a log-normal prior for integration over the nuisance parameters [40]. The resulting upper

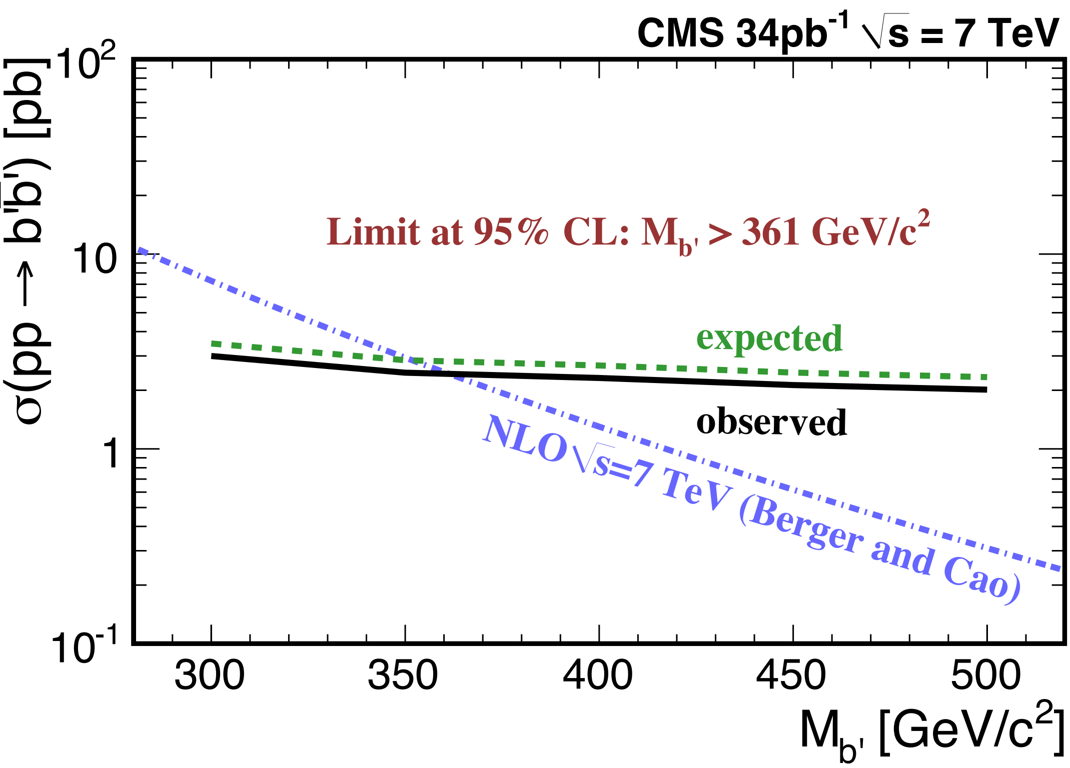

Figure 3: The exclusion limits at the 95% CL on the $pp \to b'\bar{b}'$ production cross section. The solid line represents the observed limits, while the dotted line represents the limit expected with the available sample size, assuming the presence of standard model processes alone. Comparing with NLO production cross sections, b' mass less than 361 GeV/c^2 is excluded.

limits obtained on the b' cross section are 3.00, 2.46, 2.31, 2.13, and 2.01 pb for mass hypotheses of 300, 350, 400, 450, and 500 GeV/c^2, respectively. These limits are plotted as the solid line in Fig. 3, while the dotted line represents the limit expected with the available sample size, assuming the presence of standard model processes alone. By comparing to the NLO production cross section for $pp \to b'\bar{b}'$, a lower limit of 361 GeV/c^2 is extracted for the mass of the b' quark at the 95% CL.

In summary, a search for a heavy bottom-like quark produced in proton-proton collisions at $\sqrt{s} = 7$ TeV has been presented. The production of $pp \to b'\bar{b}' \to t\bar{t}W^+W^-$ has been studied in a data set corresponding to an integrated luminosity of 34 pb^{-1} collected by the CMS detector during 2010. Final states with the signatures of trileptons or same-sign dileptons are very rare in standard model processes, and background contributions have been estimated to be very small. No events are found in the signal region defined in the analysis, and the b' mass range from 255 to 361 GeV/c^2 has been excluded at the 95% CL.

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